

Human Health/Human Factors Considerations in Trans-Lunar Space

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The human factors insights of how they are incorporated into the vehicle are crucial towards designing and planning the internal designs necessary for future spacecraft and missions. The adjusted mission concept of supporting the Asteroid Redirect Crewed Mission will drive some human factors changes on how the Orion will be used and will be reassessed so as to best contribute to missions success. Recognizing what the human factors and health functional needs are early in the design process and how to integrate them will improve this and future generations of space vehicles to achieve mission success and continue to minimize risks.

Nomenclature

<i>ARCM</i>	=	Asteroid Redirect Crewed Mission
<i>ARV</i>	=	Asteroid Redirect Vehicle
<i>CAD</i>	=	Computer Aided Design
<i>CLO</i>	=	Crewed Lunar Orbit
<i>DRO</i>	=	Deep Retrograde Orbit
<i>ECLSS</i>	=	Environmental Control Life Support System
<i>EM</i>	=	Exploration Mission
<i>ER</i>	=	Engineering Directorate's Software, Robotics & Simulation Division
<i>EVA</i>	=	Extravehicular Activity
<i>FCE</i>	=	Flight Crew Equipment
<i>G</i>	=	Gravity
<i>GN&C</i>	=	Guidance, Navigation & Control
<i>ISS</i>	=	International Space Station
<i>IVA</i>	=	Intravehicular Activity
<i>JSC</i>	=	Johnson Space Center
<i>LEO</i>	=	Low Earth Orbit
<i>MACES</i>	=	Modified Advanced Crew Escape Suit
<i>MPCV</i>	=	Multi-Purpose Crewed Vehicle
<i>MPCV</i>	=	Orion Multipurpose Crewed Vehicle
<i>O₂</i>	=	Oxygen
<i>PLSS</i>	=	Portable Life Support System
<i>TLI</i>	=	Trans-Lunar Insertion
<i>WMS</i>	=	Waste Management System

I. Introduction

TAKING into account the human element and protecting for human health is critical towards having a successful mission. Many elements of the mission contribute towards the necessary habitable volume design and planning.

The Asteroid Redirect Mission merges the Orion Program's capabilities with the Orion vehicle with the newly proposed Asteroid Redirect Vehicle (ARV) to capture and retrieve an asteroid, move to a deep retrograde orbit (DRO) around the moon, and then send a crew out to procure a sample to return to earth for sample analysis.

The Asteroid Redirect Crewed Mission is expected to leverage off the Orion spacecraft accommodations to meet the new mission design parameters. Orion has been designed to enable crew transportation missions of less than one month in duration. All of the daily habitability functions must be accommodated within the spacecraft. These

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functions include hygiene, activity planning, meal preparation, meal consumption, trash and waste management, crew exercise, spacecraft operations and communications, mission intra-vehicular activity (IVA) science, maintenance, medical care, extra-vehicular activity (EVA) preparation, EVA recovery, and crew sleep. Innovations in volume and stowage management have been necessary to accommodate all the related operational areas, supplies and kits necessary for the mission. When planning stowage, not only must there be sufficient volume to accommodate all supplies, but they must be arranged in a way that facilitates rapid and efficient crew access.

These insights and more are crucial towards understanding the internal designs necessary for future spacecraft and missions. The adjusted mission concept of supporting the Asteroid Redirect Crewed Mission will drive some human factors changes on how the Orion will be used and will be reassessed so as to best contribute to missions success. Recognizing what the human factors and health functional needs are early in the design process and how to integrate them will improve this and future generations of space vehicles to achieve mission success and continue to minimize risks. The human system integration requires taking into account assessments for crew anthropometry, biomechanics, strength, natural and induced environments such as acoustics, crew health, safety, mobility aids, crew functions and interfaces, maintenance and housekeeping tasks, information management, as well as considerations for the ground processing of the vehicle.

The Orion spacecraft which is still in development has been identified as the key crew launch and transport vehicle for future NASA missions beyond Low Earth Orbit (LEO). To better understand the human systems integration integrated into the vehicle planning, insight into the vehicle and planned layout is required.

II. Adjusting Mission Concepts and Designs

The use of the Orion crewed vehicle has changed from the original point of design to today. The first crewed lunar flight originally included Altair-based lunar sorties. In this context, the mission would have consisted of a 3-6 day traverse to the lunar orbit (docked to an Altair lander), landing on the moon's surface followed by some duration of lunar stay, returning to the Orion vehicle, transfer of the crew and release of the Altair vehicle, and concluded by

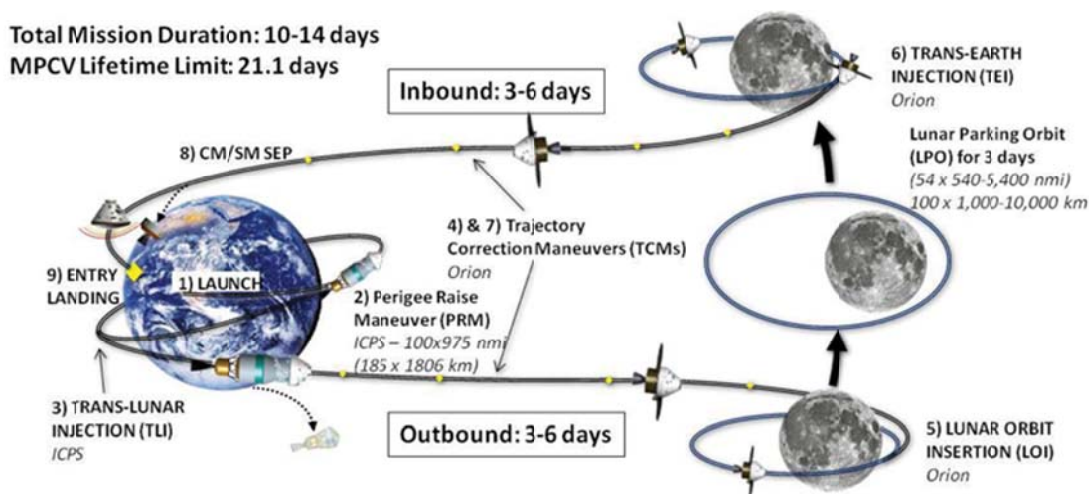


Figure 1. Original Orion EM-2 trajectory plan

a 3-6 day traverse to the Earth. Thus, barring any contingencies, the crew would have spent no more than 6 days in only Orion at any given time. The other early design mission for Orion was to serve as a crew transport vehicle to and from the International Space Station (ISS) and for these missions the crew would spend even less time in the vehicle. It was a non-validated assumption early in the Orion program that the other spacecraft's mass and volume – e.g. Altair, Lunar Outpost, Lunar Rover, ISS, etc. would provide the needed capabilities to offset the physiological and psychological deconditioning experienced in the Orion such as for exercise needs. For instance, early Crew Exploration Vehicle (Orion) Net Habitable Volume studies made the assumption that because the vehicle would only spend a few days in flight before reaching ISS, the crew would exclusively use exercise equipment and not require an exercise capability onboard the vehicle.⁴

After the 2010 cancellation of the Constellation Program and the planned lunar sortie missions, the Orion vehicle's purpose was adjusted to support Low Earth Orbit (LEO) points of interest, Near Earth Objects, lunar orbit, earth-moon Lagrange points and the ISS. Orion was asked to protect for the ability to rendezvous with additional habitation and/or lander elements in LEO to carry a crew to a near earth asteroid, Moon, Martian Moon,

or even Mars. The Orion stand-alone capability is now required to support a crew of no more than 4 for up to 21 days of active mission duration. Longer durations are possible with fewer crew. The first crewed mission (EM-2) objectives include verifications of the Orion software; guidance, navigation and control; heatshield; human-system interfaces; recovery operations and understanding/validating the effects of the space environment and technologies on human health and performance. This shorter, Crewed Lunar Orbit (CLO) 14-day mission will be the full, manned-vehicle performance assessment of the major support systems such as Air-Revitalization System, Pressure Control System, Waste Management System, Active Thermal Control, Potable Water, and adequacy of the assorted Flight Crew Equipment (FCE). The vehicle is anticipated to remain in a multi-day, high lunar orbit before returning to earth. (See Fig. 1)

The Asteroid Redirect Crewed Mission (ARCM) plans to use the Orion vehicle with two crew to transit to the Deep Retrograde Orbit (DRO) to meet the relocated asteroid, take samples, and return back to earth. This mission requires a longer duration of 25-30 days, multiple EVAs, and docking to the Asteroid Redirect Vehicle (ARV). (See Fig. 2)

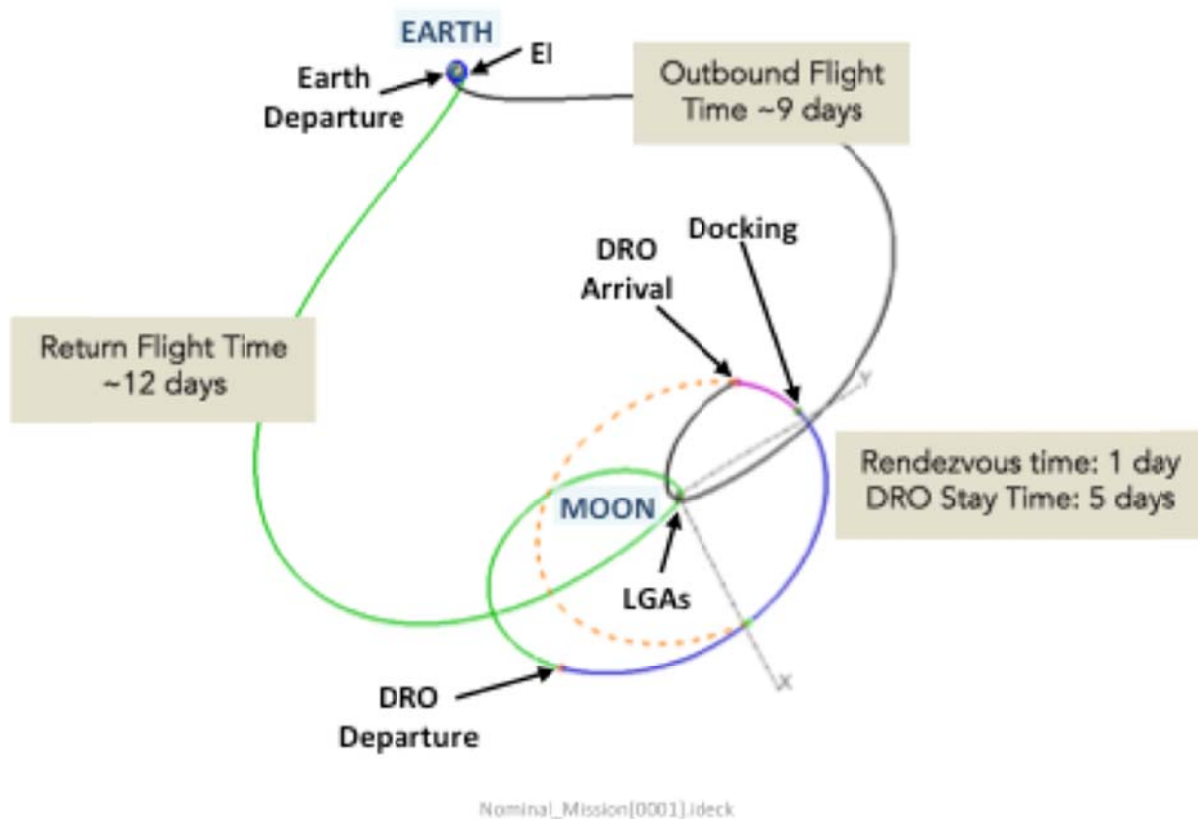


Figure 2. Asteroid Redirect Crewed Mission Trajectory Overview

Due to the Orion's limitations for mass, volume, and the additional supplies required to enable this mission, the four crew vehicle will be reconfigured to support two crew. The reduction in crew supplies and logistics frees up available mass and volume for ARCM specific needs such as the launch/entry suits modified to support EVAs (MACES), the portable life support system (PLSS) backpacks to allow spacewalks away from Orion, and the science sampling tools.

In order to best understand the changes required to support the ARCM mission, it helps to understand the details of the Orion habitation design and how the Orion design compares to other space-flight vehicles.

III. Orientation to the Orion Vehicle and Habitation Design

The Orion spacecraft consists of the Launch Abort System (LAS), Command Module (CM), and Service Module (SM) (See Fig. 3). The habitable volume of the spacecraft is contained within the Command Module (See Table 1[†]_{‡§**}). This cabin area is divided into four main areas: the docking tunnel, crew seating, stowage volumes and hygiene facilities (See Fig. 4).

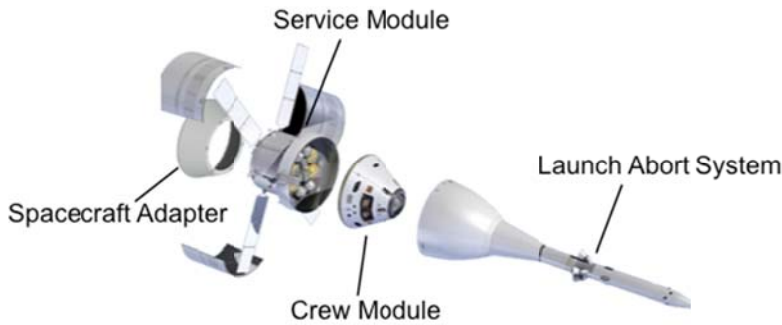


Figure 3. The Orion vehicle spacecraft with major subsystems identified

As with the Apollo CM, the crew seating area occupies the majority of the central volume of the spacecraft supporting launch and landing seating for up to four crew members. The seats will be arranged on individualized seat mounting similar to what is shown in Figure 3. Upon exiting low earth orbit, the second row seats are planned to be stowed and the first row seats will have the calf and foot rests removed to reconfigure the cabin for the

daily activities. The first row seats initiate, support and monitor the mostly autonomous vehicle command and control activities needed for the Orion vehicle such as communications, guidance and navigation systems, power systems, environmental control systems, and caution and warning.

During the coast period, most of the spacecraft systems perform their functions automatically and autonomously from any crew or ground action. Some exceptions include periodic spacecraft guidance platform realignments using the star trackers and the state vector updates by the MCC. There may also be mid-course corrections to the trajectory required to assure the spacecraft remains on the proper trajectory.

The tasks identified for the crew during the transit will include mission specific tasks (such as verifying the status of various Orion systems) and the common tasks such as meals, exercise, hygiene activities and conferences with the ground teams. The arrangement of the interior cabin is meant to optimize access for similar activities planned to be done during nominal Orion activities.

Mission specific tasks are likely to require the crew to access items in the various stowage locations. Stowage volumes are located primarily beneath the crew seating area. Cabin secondary structures divide these volumes into six distinct areas which may be subdivided further into individual stowage lockers, bays or other structures. The centermost stowage volumes are sufficiently large that if emptied, one or more crew members can fit inside the bay. (See Fig. 5). The stowage areas will include much of the portable items

Table 1: Space Vehicle Habitable Volume Comparison

Vehicle	Number of Crew	Duration of Mission	Habitable Volume (m ³)
Orion	4	Up to 21 days	9.4
Orion with ARC Mission	2	Up to 30 days	9.4
Apollo	3	Up to 14 days	6.2
Soyuz	3	Up to 30 days (longest flight with 2 crew was 17.5 days)	8.5
Skylab	3	Up to 84 days	361

[†] <http://www.hq.nasa.gov/alsj/a15/a15prskit.html>

[‡] <http://www.spaceflight101.com/soyuz-spacecraft-information.html>

[§] <http://www.spacefacts.de/mission/english/soyuz-9.htm>

^{**} <http://www.space.com/21055-skylab-space-station-nasa-infographic.html>

(generally called Flight Crew Equipment) such as food, water, clothing, toiletries, stowage bags and bungees, medical kits, radiation monitors, cameras, and survival gear which complement Orion vehicle equipment and consumables.

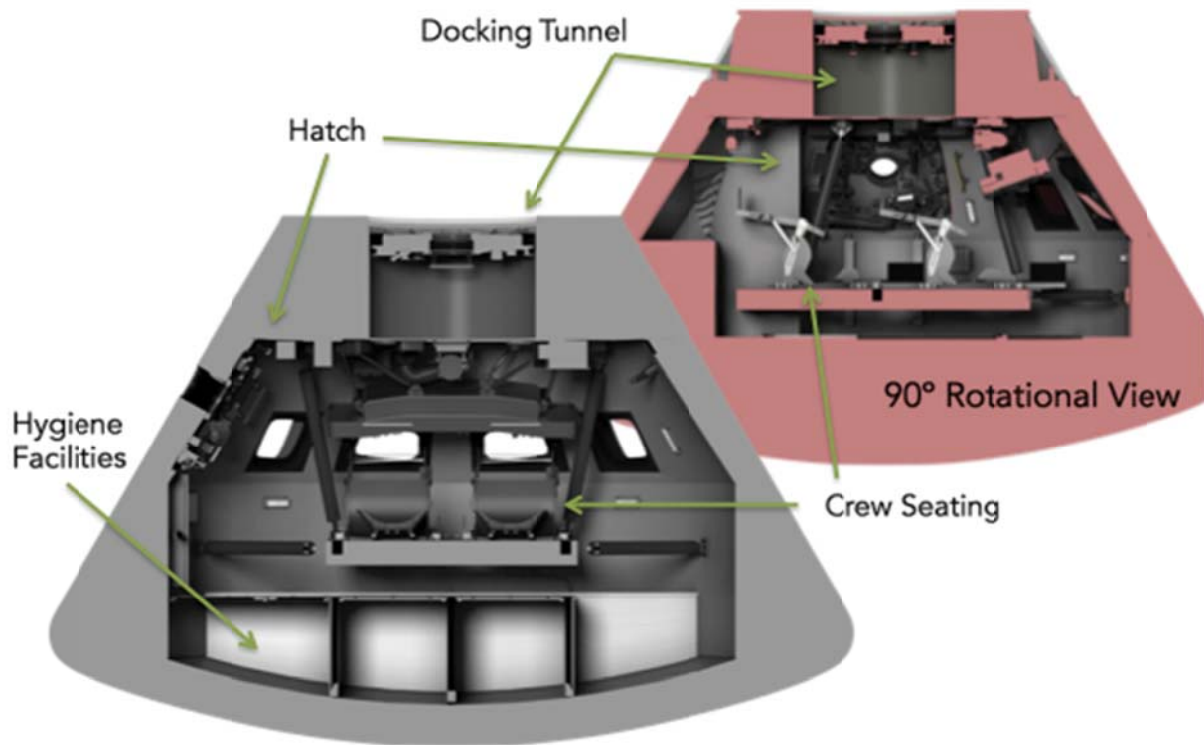


Figure 4. Orion Command Module layout showing hatch locations, docking tunnel, windows, crew seating and location of hygiene facilities

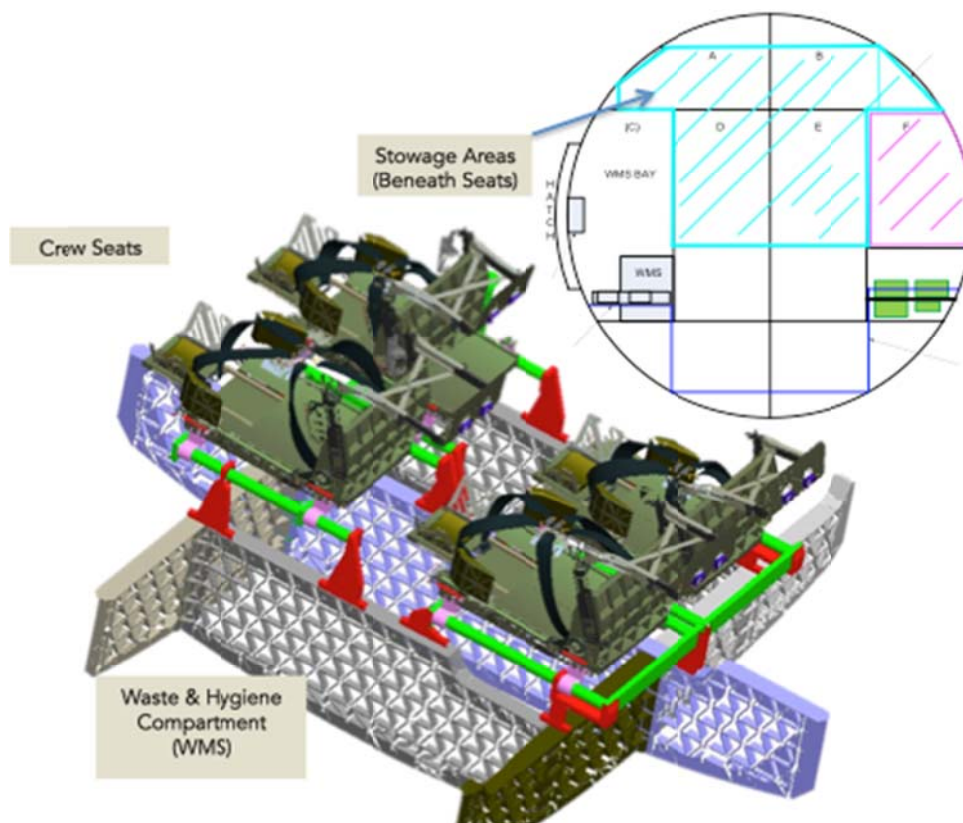


Figure 5. Crew Seats, Hygiene area and Stowage compartments within the Orion vehicle

A. Hygiene Volume

The crew hygiene facilities consist primarily of a toilet improved from the Shuttle and ISS design and occupies the stowage volume immediately beneath the hatch. Figure 6 shows a low fidelity mockup of the hygiene facility. Only one crewmember can fit inside the facility at a time. The facility is also meant to provide privacy and support both men and women crew.

B. Sleep Volume

The crew sleep areas are expected to be located throughout the operational volume of the Command Module without blocking the hygiene facility. (See Fig. 7) During the crew sleep period, the vehicle is supposed to operate in a manner so as not to interrupt crew sleep – such as preventing loud noises and providing window shades to allow for darkness inside the cabin. The crew will deploy thin sleeping bags which they will be restrained to structure to keep them in an approximate location while sleeping and allow for sufficient space for normal sleep movements.

C. Meal volume

Mealtime is likely to be a coordinated joint activity for all the crew. Food is planned to be stowed under the front two seats and will need to be retrieved for each meal. The ambient water port used to rehydrate the food is located in the front right corner near where the food warmer will be stowed. The current plan is to use the ISS food warmer which allows it to be relocated within the vehicle and passed between crew. Once meals are finished, the trash is expected to be stowed where the items were pulled from. (See Fig. 8)

D. Exercise Volume



Figure 6. Low fidelity mockup of the hygiene facility within Orion

Due to the drastic physiological changes seen during space-flight, exercise is a necessary component for crew health in space. The location for the exercise activities has yet to be formalized, however the prime candidate location is expected to have the equipment mounted under the side hatch with the operational volume angled up towards the top hatch area. The exercise identified as being needed for the Orion is a device that can provide both rowing and resistive exercise up to 350 lbs load, so as to aid in recovery of aerobic capacity and protect for the ability to egress the vehicle upon landing while wearing the MACES suit. As per Figure 12 the operational volume needed to accommodate the anthropometry range of crewmembers and an exDAAercise device throughout the needed crew movements while floating in space requires about 5 m³ which would be about 54% of the available habitable volume space.

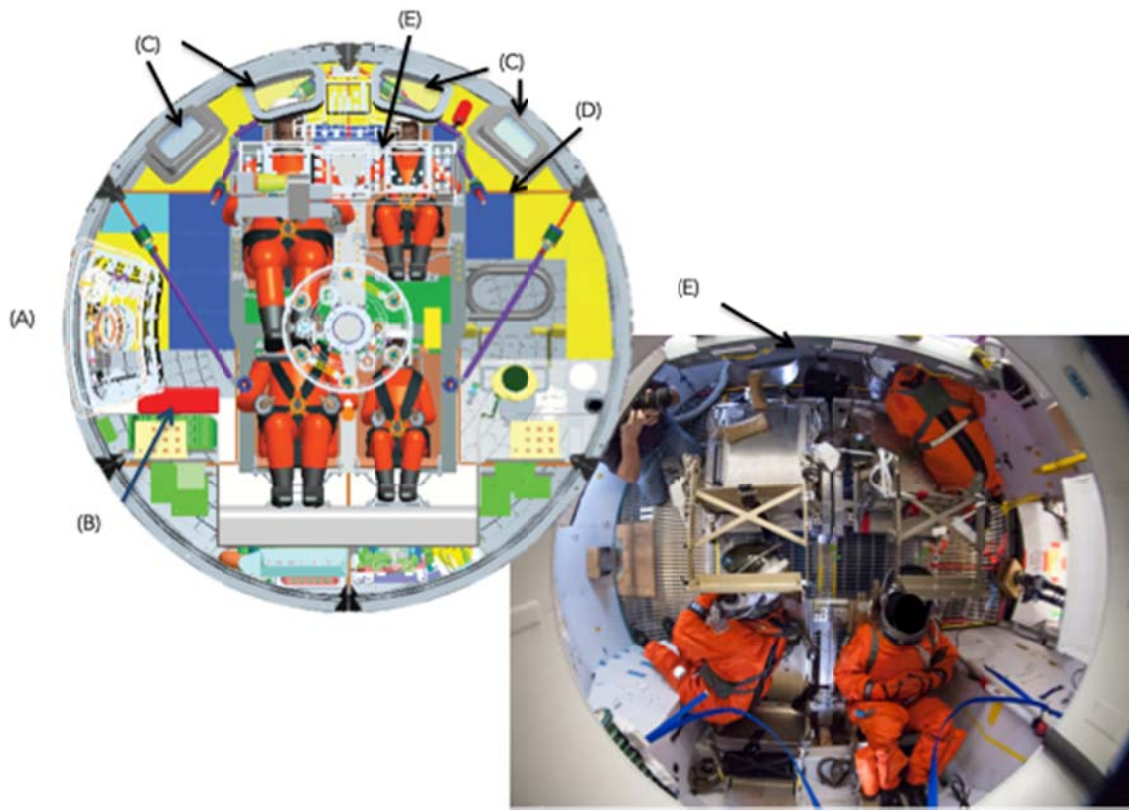


Figure 8. View looking down into the Orion Command Module from the docking hatch with photo of fit check assessment activities of same view. (A) Side Hatch, (B) Life Raft & Survival Kit Planned Location, (C) Windows, (D) Water Dispenser, (E) Control Panels

E. Contingencies Volume

Although every effort is made to avoid any contingency situations, certain scenarios are deemed necessary to provide adequate response measures in the event they should occur. These emergency related items include fire extinguishers, medical kits, breathing masks, liferafts, and survival kits. (See Fig. 9) The fire suppression system and water cooling systems are located in the Environmental Control and Life Support System (ECLSS) bay. In order to protect for rapid access during an emergency egress situation, the life raft and survival kit are planned to be located on the ECLSS wall closest to the side hatch. If the sea conditions make egress through the side hatch untenable, a ladder has been made available to the crew in the top hatch area along with a wench to aid lifting and lowering the top hatch door. Other crew health issues that might require rapid access will be addressed by the medical kit and breathing masks which are planned to be mounted on the opposite ECLSS wall for easy access.



Figure 9. Potential location of contingency equipment opposite side hatch in low fidelity mockup

IV. Evaluation of Mission Timelines

In order to effectively evaluate the completeness of the interior designs, it helps to walk through potential mission timelines. In addition between the various activity zones, the Orion is being designed so as to protect for translation paths between operational areas despite the limited volume.

Although still in the process of being developed, Orion's EM-2 timeline will likely be focused on providing system validation of vehicle systems and performance during flight. On the flight day, the suited crew will enter the vehicle and be secured for launch. After launch and entry into microgravity, the crew will confirm the performance of various subsystems before proceeding with the Trans-Lunar Injection (TLI) maneuver to direct the vehicle towards the Moon. After the maneuver, the crew will reconfigure the cabin for the extended mission. The first of several video conferences is likely to be scheduled shortly thereafter. In between, the standard daily activities of meals, exercise,

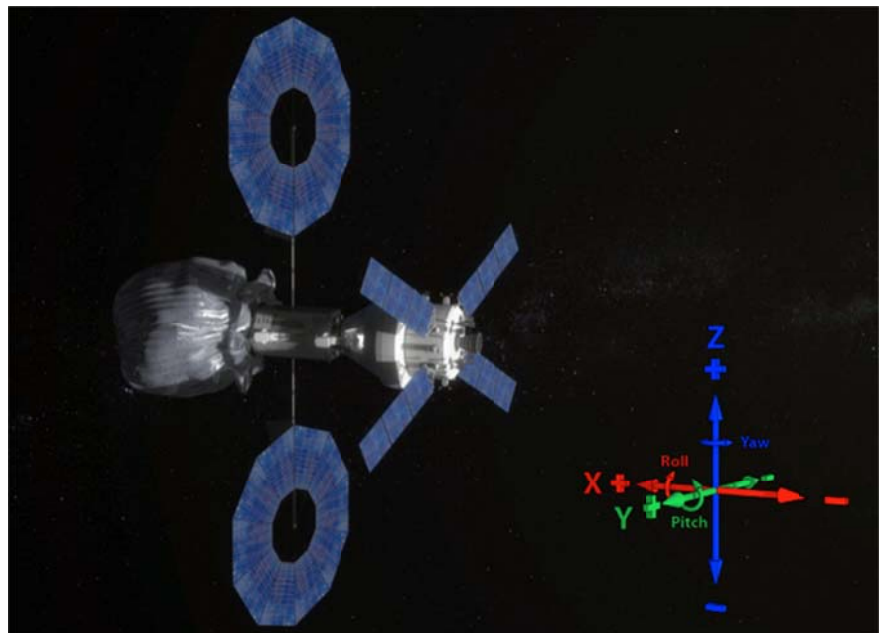


Figure 10. Asteroid Redirect Vehicle with the Asteroid docked to the Orion with the related coordinate system

hygiene and sleeping, the crew will likely be asked to perform a series of system checkouts confirming everything works as intended. During the mission, at least one of the crew will monitor critical vehicle operations. When returning to Earth, the crew will need to reconfigure cabin and the vehicle for the re-entry so as to protect for the safety of the crew.

The ARCM mission timeline will start off similarly to the EM-2 timeline through launch, ascent and the trans-lunar insertion (TLI) burns. As with EM-2 there will be standard crew activities such as meals, hygiene, exercise, and sleep that are unlikely to change significantly from the previous mission. With the smaller complement of two crew, the necessary vehicle activities are likely to be reallocated differently than EM-2. The available space per crewmember may not be that much greater per crewmember than EM-2 due to the additional stowage requirements to support the ARCM required capabilities and additional consumables required for the longer 24-30 day mission.

The variations will likely start with activation and checkouts of any mission unique equipment prior to rendezvous with the Asteroid Retrieval Vehicle (ARV). (See Fig. 10) For example the crew is likely to be asked to perform an EVA suit checkout and internal dry run during the 7-9 day transit period out to the ARV. The crew is also likely going to be asked to go through the rendezvous and docking activities to confirm operational readiness. Depending on the independence of the vehicle controls, the Lunar Gravity Assist maneuver and the docking may require command and control inputs from the crew. Upon docking with the ARV, the crew will confirm the stacked vehicle configurations are as expected and the now integrated systems are performing as planned prior to embarking on the first EVA to the asteroid. The crew will need to stow and secure loose items, suit up within the Orion habitable volume, depressurize the module, and then exit through the side hatch. The interior design, placement of equipment, stowage areas and open volume will need to be able to withstand the pressure changes, vacuum exposure and not create any undue safety hazards for the crew during the unpressurized phases of the mission.



Figure 11. Conceptualized image of crew exiting Orion and installing their translation boom during an EVA

Two four-hour EVAs are planned. The crew may be asked to secure their translation guides (such as translation booms and handrails), deploy antenna to relay the biometric, suit health status, voice & video data from the Exploration PLSS radio to the ground via the Orion S-Band system, identify the best locations for sample retrieval, retrieve tools flown with the ARV, preposition any tools, sample collection containers, and location lighting that will be needed during sample collection at or near the site, perform the collection, assemble the samples into the transit container, translate back to the Orion module, ensure the hatch seal area is free of debris, loose rocks or damage that could prevent an effective seal, close the hatch, and repressurize the vehicle, and possibly cycle the atmosphere to clear of any floating debris prior to doffing the crew suits. (See Fig. 11) The five docked days are meant to provide sufficient time for both EVAs, and – if needed – a third EVA. During this time there will be multiple days of

communication dropouts due to a combination of mission attitude requirements and blockage caused by the ARV solar arrays with the asteroid, so the crew will need to be sufficiently independent so as not to require communication during those periods. Between EVAs, the crew will need to service and checkout the equipment including recharging the suit and tool batteries, cleaning the suit interiors, replacing biomed sensors, and checking out Exploration PLSS components. Also, depending on the structural and GN&C assessment, exercise may be suspended during this docked period so as not to cause any vehicle structural damage or undue thruster firings to maintain attitude.

After the five days, the vehicle will undock from the ARV, and during the 12 days of return transit, the crew will stow the EVA equipment and samples and prepare for return. Again, if there is any crew assist needed for the vehicle command and controls during undocking and the Lunar Gravity Assist maneuvers, the crew will prepare and implement the operational steps to support the activities. Upon approach to reentry to Earth, the crew will stow any remaining items, don their protective MACES suits, and return similarly to the EM-2 mission. (See Table 2)

A comparison of the two different timelines will show that there are fundamental differences in how the Orion vehicle will be used for the different missions. Some aspects –

such as a smaller crew of two – may make internal operational plans easier, while others – such as suiting up and using the Orion capsule as an airlock – are likely to add additional complexity to planned mission operations.

Table 2. Planned ARCM timeline

Flight Day	Event
1	Launch, Ascent, TLI
2-5	Outbound Translunar Cruise. Suit checkout/EVA dry run, rendezvous/docking preparations
5	Lunar Gravity Assist and Lunar close approach
5-7	Lunar to DRO Cruise
8	Rendezvous and Docking
9	EVA 1
10	Suit refurbishment, EVA 2 prep
11	EVA 2
12	Contingency margin, Housekeeping, Departure Prep
13	Undock and Departure
13-19	DRO to Lunar Cruise
19	Lunar Gravity Assist maneuver
20-26	Inbound Translunar Cruise, cabin stow
26	Entry, crew recovery

V. Human Factors Design Technical Challenges

A. General Design

Engineering the vehicle design to incorporate the crewed volume while minimizing mass and volume impacts is not an easy task. Multiple systems have to be planned for and integrated to provide the needed access and control points when needed while minimizing the piping, cabling and other structural adaptations needed so as to reduce routing and improve access to the needed operational locations. For example, the umbilical routing for air delivery to the MACES suits are being assessed for the most efficient routing. Current plans would require about 44 ft. configured to reach each crew around the seats and to avoid snagging.

In 2013 some human-in-the-loop (HITL) testing with a mockup of the Orion vehicle was conducted to evaluate the impact of changes to the seat attachment and attenuation system especially in the areas of crew egress and habitability. The teams assessed impacts to major systems such as WMS access, volume, and obstructions, stowage locker accessibility, radiation shelter entry/exit, exercise locations, and post-landing ready-access water locations. These assessments helped to inform emergency equipment re-locations and whether proposed internal configuration changes were viable.

The updated EM-2 mission and the supporting validation activities will continue to inform and identify other potential adjustments needed to accommodate the mission concept changes for the vehicle from the original concept.

B. Stowage

All of the flight crew equipment must be safely stowed or restrained for launch, launch aborts, and entry. This equipment includes everything the crew needs that the vehicle does not otherwise provide, such as food, change of clothes, laptop, or solid waste containers. All these items must be volumetrically accommodated within the spacecraft. Because of Orion's small size, the available stowage volumes are irregularly shaped. The items to be

stowed within Orion are also non-uniform in shape. This creates organizational challenges to find a logical allocation of equipment to the available Orion stowage volumes.

One important consideration is accessibility. When crew members need to access a particular item, it is helpful to minimize the amount of other stowed items that must be moved in order to gain access to the item in question. This is particularly important with respect to management of small items. One driving design consideration is the crew access of equipment after splashdown. The crew will be physiologically deconditioned after several weeks in microgravity and the spacecraft will be floating on the ocean, thus subject to disorienting and disruptive wave motion. The crew may need to access emergency equipment under these conditions. They should not need to unstow unnecessary items to access post-landing equipment nor should they need to assume difficult postures to do so.

Separation of food and waste is another design driver for stowage. Orion begins the mission with a large quantity of stowed food and no human waste. By the end of the mission the food volume has been largely consumed and there is a large quantity of human waste and trash, but it is unpalatable to stow the human waste where the food is stowed, leading to a driver for management of both food and waste stowage volumes.

The ARC mission requires mission-unique items to be stowed either within the standard cabin stowage volumes beneath the seats or on cabin mounts. These items include equipment to support the EVAs and the sample return container. A feasibility study was conducted to assess whether the ARC mission equipment would fit within the remaining volume left after accommodating the typical Orion flight crew equipment for this crew size and mission duration. Volumes of both sets of items were increased by 30% to account for packing inefficiencies (typically 20%) and an additional uncertainty of 10%. The total adjusted volume of all stowed items for the ARM were within the total stowed volume the vehicle can accommodate. As the ARM planning matures, it will build off of the EM-2 stowage work to examine which bays the ARM equipment would fit within while meeting the other design considerations previously described.

C. Exercise

Exercise in general can be difficult to include in vehicle design. In order to understand how best to integrate exercise activities, it helps to understand the reason exercise is needed during spaceflight. Throughout the first four to six weeks the human body goes through an acute adaptation period to the microgravity environment that affects many physiological systems. (See Table 3) For example, muscular strength decreases rapidly during this adaptation period. (See Fig. 12)

The decrease in muscular strength could keep the crew from successfully getting to safety in an off-nominal Orion landing event or having sufficient endurance to conduct successful EVAs. The International Space Station crew actively exercises 1.5 hours six days of every week to recover from the effects of spaceflight. Operationally Orion could support up to an hour per crew per day for four crew, however the protocol objectives are to complete the required exercise needed in 30 minutes per crew per day. Exercise is primarily used to counteract the muscle and aerobic losses experienced in the on-orbit environment; however, exercise requires a relatively large operational volume within the vehicle. Of the many vehicle design integration aspects required to incorporate exercise, some of the most difficult to accommodate can be identifying the space required to allow for crew movement with the equipment and designing atmospheric systems that can process the higher CO₂, heat, and humidity created during exercise.

Table 3. Mean percent change on Shuttle landing day from pre-flight mean, for skeletal muscle and concentric and eccentric strength of various muscle groups (average duration of 10 days).⁵

Muscle Group	Test Mode	
	Concentric	Eccentric
Back	-23 (+/- 4)*	-14 (+/- 4)*
Abdomen	-10 (+/- 2)*	-8 (+/- 2)*
Quadriceps	-12 (+/- 3)*	-7 (+/- 3)
Hamstrings	-6 (+/- 3)	-1 (+/- 0)
Tibialis Anterior	-8 (+/- 4)	-1 (+/- 2)
Gastroc/Soleus	1 (+/- 3)	2 (+/- 4)
Deltoids	1 (+/- 5)	-2 (+/- 2)
Pects/Lats	0 (+/- 5)	-6 (+/- 2)*
Biceps	-6 (+/- 6)	1 (+/- 2)
Triceps	0 (+/- 2)	8 (+/- 6)

* Preflight >R=) ($p < 0.05$); $n=17$. Landing day (R+0) versus average of 3 preflight measures.

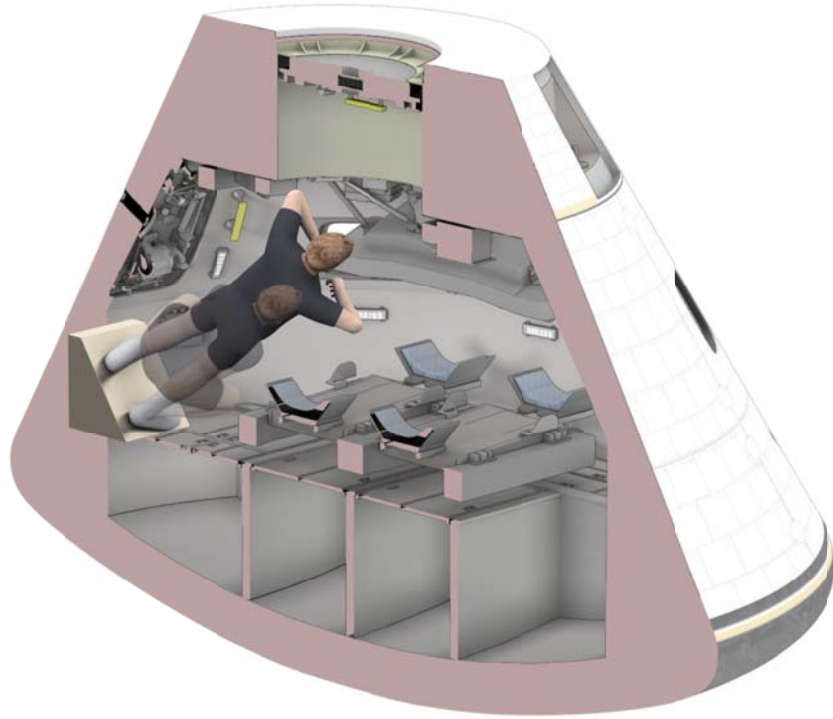


Figure 12. Exercise location may place the device under the side hatch. Crew height (illustrating rowing motion) represents 99th percentile anthropometry.

Today's Orion environmental control constraints limit the duration of exercise to approximately 30 minutes of time in every 90 minute period. Structural assessments have identified that exercise mass movement will not adversely impact the external structural components such as the solar arrays. Guidance, navigation and control teams have identified that the planned exercise may require some infrequent, trivial system thruster responses to



Figure 13. Conceptualized placement of the exploration PLSS in the place of seats 3 and 4 in the Orion Command Module

maintain attitude.

The impacts of the change of mission concept on exercise from short excursions to a habitation vehicle for 21 days is still being accommodated. Some of the near term challenges for the various teams is to assess what can be done to effectively protect the crew from the deleterious effects of spaceflight given the mass and volume constraints of the vehicle. No known exercise devices have been identified that can meet both the physiological performance parameters and the identified mass and volume limitations, so future engineering design challenges exist for the teams.

The longer and more strenuous ARCM will require slightly more conditioned crew so as to protect for the endurance capabilities for the planned EVAs and protecting for Orion's 6-G reentry after a longer duration mission.

D. Impacts to Human Factors of adding the ARCM kits

The Asteroid Redirect Crewed Mission will bring multiple changes to the vehicle. Significantly, the crew size will reduce from 4 to 2 and the mission duration will increase from a maximum of 21 days to a nominal mission of about 30 days meaning that the amount of resources to support the crew will scale accordingly. The added duration and added activities will require additional mission "kits" that will provide the needed capabilities such as EVA suits, science collection equipment, ARV docking equipment and additional vehicle communication hardware. Any kits that cannot be stored in the freed up stowage volume will be stowed in and reduce the net habitable volume. Additional operational space assessments will need to be done to confirm that the volume can still support the planned activities and in addition not interfere or provide snagging points for using the interior of the vehicle as an airlock. The EVA repress kit will require positioning within the stowage volumes so as to allow for access to the airflow conduits while providing ease of access to the repress valve while suited inside the cabin volume. (See Fig. 13)

E. Impacts of the addition of the Asteroid EVAs

Once docked to the ARV, the human system design incorporated into the planning will facilitate the EVA activities and minimize the risks to the crew. The improvements needed to offset the challenges with reconfiguring the MACES into an EVA capable suit including donning and doffing are areas that will need to be designed and developed. Translation boom design planning that improves ease of attachment as well as securing it in the best location in relationship to ingress and egress from the Orion hatch will minimize initial setup time and return time. The design and placement of EVA tools and sample collection devices will protect for more crew time to access the asteroid and respond to unforeseen situations while protecting against potentially sharp debris. (See Fig. 14)



Figure 14. Conceptualized graphic of an EVA sample collection from the asteroid

F. Contingency Challenges

While some aspects of contingency planning seem obvious – such as positioning equipment where it can be conveniently accessed, other concerns are not as obvious. One of the challenges in a small space vehicle is protecting the crew from radiation events. Should an event be detected in time, the plan is for the crew to shift equipment and take shelter in the central stowage compartments under the front two seats. The removed stowed items would be placed around them to add additional protection until the event subsides. Cabin design and planning for this event includes assessing air flow into the stowage compartments to prevent localized CO₂ buildup.

Protecting for medical events not only includes effective planning on what is being flown, but also planning for the operational space needed to provide access and care to an ill or injured crewmember. The amount of medical capability is based on a combination of duration of the mission, complexity of the mission and access to additional care. Orion nominal operational plans require a Level III level of care (See Table 4).

Table 4. Medical Care Capabilities and Level of Care

Level of Care	Mission Capability
I	LEO < 8 days Space Motion Sickness, Basic Life Support, First Aid, Private Audio, Anaphylaxis Response
II	LEO < 30 day Level I + Clinical Diagnostics, Ambulatory Care, Private Video, Private Telemedicine
III	Beyond LEO < 30 day Level II + Limited Advanced Life Support, Trauma Care, Limited Dental Care
IV	Lunar > 30 day Level III + Medical Imaging, Sustainable Advanced Life Support, Limited Surgical, Dental Care
V	Mars Expedition Level IV Autonomous Advanced Life Support and Ambulatory Care, Basic Surgical Care



Figure 15. An example mobility aid to assist the second row crew to exit their seats

The ARCM mission introduction of EVAs also introduces additional medical contingency planning. Medical is a perhaps understated impact of adding EVAs. EVAs can create physical trauma that can require minor medical treatment. Specific injuries related to EVAs can include decompression sickness, shoulder injuries, fingernail trauma, and other hand injuries. These injuries are not likely to occur during IVA activity and therefore may not be addressed by the Orion medical outfitting planned for EM-2. Orion's planned medical kit contains medicine, first-

aid supplies, and basic life support equipment for minor medical situations not requiring extensive treatment. EVA-related injuries cannot be mitigated through crew selection and may require the appropriate hardware to be added to the medical kit or adoption of a risk posture to not treat injuries incurred as the result of nominal EVA operations.

Upon an off-nominal landing event that would cause issues such as problems with maintaining the Command Module's floatation or providing a toxic interior cabin environment, the crew would need to rapidly egress the vehicle. Vehicle design planning to protect for this capability requires that the activities such as configuring the crew's survival gear, deploying the life raft, and egressing the side (or top) hatch also needs to take into account the aerobically and muscularly deconditioned crew that may be experiencing orthostatic intolerance effects. Exercise is meant to help mitigate the aerobic and muscular deconditioning, while other mitigations are being investigated to mitigate the other orthostatic intolerance effects. Mobility aids are being assessed (See Fig. 15) to help crew exit their seats.

G. Sleep Locations and Meal Planning

Although several approaches are being reviewed, there are no defined locations for crew sleep or meal planning. For crew sleep it is assumed that crew members will strap crew restraints to random surfaces of the cabin. Limited CAD modeling demonstrated that it is possible to position four crew members in sleep-like postures. However, many factors that have not yet been modeled will drive which sleep positions are actually viable, such as internal temperature variations, humidity, noise, and lighting.

Given the small size of the vehicle volume, there is no constraint to maintain meal consumption within a specific distance of meal preparation equipment. Consequently, cabin configuration for meals will be a matter of crew preference. The primary constraint will be mitigation of task interference between crew member(s) responsible for meal preparation. This will likely mean that any meal preparation or clean up is done in an area that is not used for access to vehicle displays and controls, nor the WMS, nor exercise. This suggests either the aft bulkhead, or the ceiling above the WMS, or potentially a corner outboard of the display and control panel. Crew dining locations will probably vary from crew to crew, and possibly from meal to meal, but when all four crew eat as a group the center of the cabin volume will likely be a popular volume. When individual crew members eat alone, they will probably find the most comfortable, "out of the way" corner to occupy.

H. Trash

The plan for trash management is also still in developmental stages. Crew waste is expected to use the same WMS cans with charcoal odor filters that were used successfully on Shuttle. Food disposal plans are still in work to identify effective storage solutions that can contain both the trash and the odors effectively as Orion does not have the constant ventilation system that kept odors down in Shuttle. Stowage teams will also need to identify how to manage trash location so that food is kept apart from waste and other trash items. The trace contaminant control system may be able to help remove odors from the compartment, but will not limit the odors at the sources of the concerns – nor is the level of performance capability well understood just yet.

VI. Adjusting to New Mission Paradigms

There are particular philosophies that consciously or subconsciously guide the assumptions and decisions that are made by engineers within any given industry. Within the space industry there are a number of paradigms that have formed as the result of more than fifty years of human spaceflight. However, these paradigms are shaped by particular experiences that are not valid in all spaceflight architectures. The majority of human spaceflight experience is within Low Earth Orbit, which has given rise to paradigms that may be harmful in missions taking place beyond this regime.

In flight maintenance philosophies have been heavily driven by our LEO experience. The Space Shuttle program employed a philosophy known as Redundancy Management (RM), where the Orbiter spacecraft employed functional redundancy in all critical systems, such that if any given component failed there was a backup component ready to take over its function. Flight rules were established to determine how long the vehicle could rely on backups and once a particular threshold was crossed, the crew was required to immediately prepare the vehicle for deorbit and conduct a mission abort. Multiple runways were on standby around the world, such that the crew could return home at any time. Once on the ground, the Orbiter would be repaired and placed back in the launch preparation flow.

The International Space Station cannot land, so unlike the shuttle it employed an Orbital Replacement Unit (ORU) philosophy. In this case, should any component fail, either the function would be suspended or a backup would take over. Meanwhile, a replacement would be scheduled for installation – whether the replacement unit was

already on the station or it needed to be launched on an upcoming logistics resupply flight. In the event of a failure that left the station uninhabitable, it could always be abandoned with the crew taking a docked spacecraft to land on Earth.

Both RM and ORU philosophies break down beyond LEO. At a DRO, trajectories are constrained both by distance and orbital phasing. There are specific windows where spacecraft can transit back to Earth. Unlike the shuttle, an Orion at a DRO is days away from an Earth return and cannot operate with nonfunctional critical system during a return cruise. Also unlike the ISS, the Orion will not receive regular logistics resupply flights. Thus, a new maintenance philosophy is needed that will be appropriate to Orion missions in DRO.

A similar challenge is faced in the area of crew health. Both ISS and Shuttle enjoyed the luxury of their proximity to the surface of the Earth. Hospital-quality medical care was never more than 72 hours away for an orbiting space crew. At DRO such medical care is as much as one to two weeks away from the point of declaration of an emergency. This implies the need to develop a new paradigm for the maintenance of crew medical care.

What is the philosophy on trash? Shuttle missions were typically 14 days or fewer and trash was stored in specialized compartments, some of which used vacuum venting as a method of odor control. ISS stores trash in logistics modules which periodically undock from the station and are disposed of by burning them up in the atmosphere. Orion cannot offload trash to other modules and the capsule does not have any form of vacuum venting or other odor control methods.

Finally, the confinement experienced by Orion crews is unlike prior human spaceflight experience. Both Skylab and ISS missions have exceeded ARM missions in duration, but with considerably greater habitable volumes and much more diverse crew tasks. The physiological and psychological challenges of the much smaller Orion capsule presents unknown challenges. Apollo crews (and some shuttle crews depending on internal outfitting) experienced similar volumes as Orion, but for much shorter missions. New paradigms in this arena may impact not only crew selection but also crew timelines.

VII. Operational Validation

In order to validate the operational plans and identify additional technical challenges, human factors and human systems engineering assessments have been performed simulating key mission tasks such as crew ingress, emergency egress and various systems configurations. As these assessments are done, critical performance factors are identified that occasionally lead to internal systems modifications. For example, under the new mission concept, the crew will use the Orion vehicle as an airlock, so room must be available and equipment configured so as not to damage the MACES EVA suits upon egress and entry for all the crew. As those same suits are the safe haven for a cabin depressurization event, the suits must also be designed for rapid donning by all crew before the Orion ECLSS system loses the ability to maintain cabin pressure.

Several methodologies exist that can inform design planning and validate that intended performance criteria were met. Historical data from similar spaceflight programs can qualitatively help in assessing planned numbers in a vehicle design – if both the historical data and design data are well understood for their similarities and differences. This historical data is often incorporated for use in parametric assessments which can be used to qualitatively rate the planned estimates. A “bottoms-up” assessment may be used once enough fidelity in the planned implementation is defined wherein known capabilities are defined and understood to the individual items and specific implementation details and then integrated up through the various subsystems to provide a vehicle level integration picture. Example analog missions may be used to validate design planning and performance once subsystem components are available for assessment or when operations are sufficiently defined. Analog mission activities can drive consideration of crew timelines and activities in ways that can be otherwise overlooked during design studies. They can also reveal critical architectural gaps before vehicle maturity has progressed to the point where corrective measures can become prohibitively expensive. For instance, there may be conflicts between crew exercise, mission science, WMS usage, and spacecraft operations that may not show up during standalone human-in-the-loop evaluations of the cabin. However, during a multi-day analog mission evaluation the crew is responsible for completing a specific set of science objectives while responding to spacecraft operation tasks, conducting daily exercise, using the WMS, eating, sleeping, and conducting other habitation tasks. In such a scenario it becomes readily apparent when vehicle configuration (volumes, layouts, orientations, and co-locations) negatively impacts crew productivity or safety. Vehicle mock-ups depending on fidelity to planned equipment may provide a 1G insight into operational space, organization, accessibility, and other vehicle system aspects that may be difficult to assess in models.

However models play a critical function in vehicle design and planning. A recent assessment incorporating higher fidelity equipment models into the vehicle model identified additional habitation volume was needed for

wiring and tubing that had changed from previous configurations. A brief assessment with the crew helped to identify the best locations for the pathways and corresponding wall updates so as to minimally interfere with planned operational volume usage. (See Fig. 16)

Several tools have been developed to perform virtual configuration analyses. For example, the Orion team has developed a computational fluid dynamics model to perform airflow analyses and CO₂ removal for various internal configurations. The model is validated during chamber tests to confirm model predictions match actual observations. A CAD model was used to perform initial stowage assessments and evaluate mass distribution within the capsule.

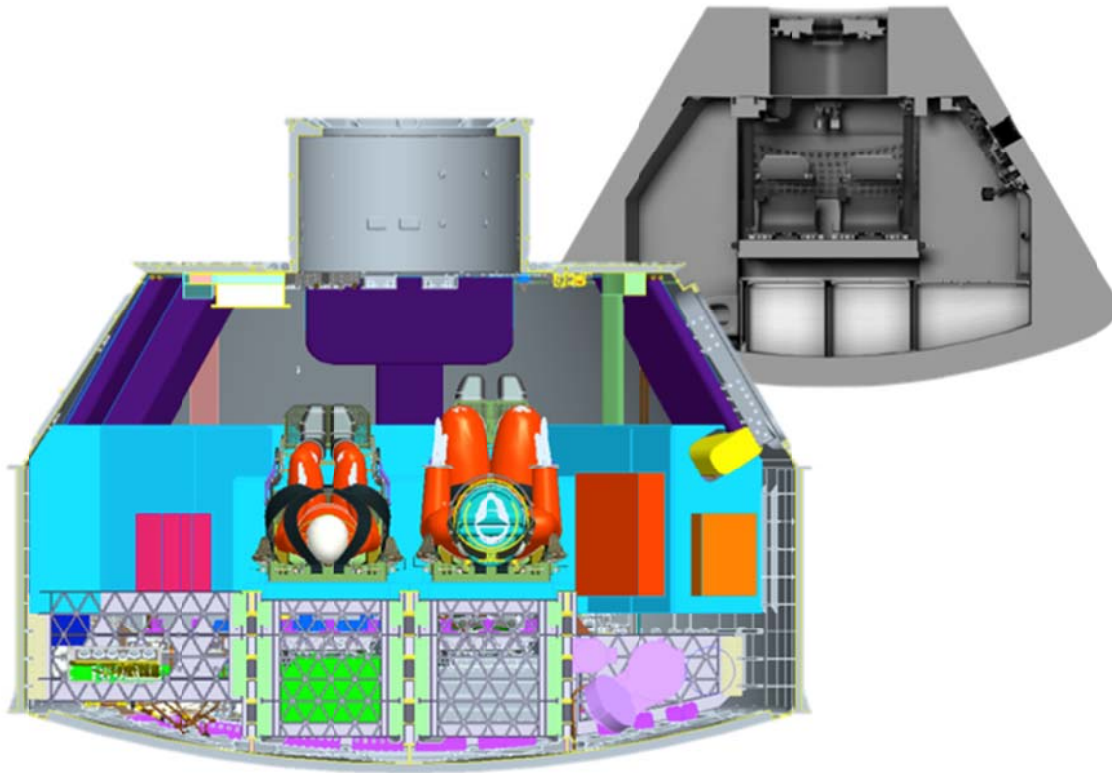


Figure 16. An illustration of proposed habitation volume changes for the interior of the Orion Command Module. Colored graphic shows the latest adjustments to the back wall, addition of emergency equipment (orange and red boxes), and relocation of WMS to underneath the hatch.

The low fidelity mockup has been very useful for the Orion team to acquire qualitative insights to identify any major design concerns in a low cost and rapid schedule manner. The timeliness of the responses also supports the vehicle designers development schedule well so that adjustments – especially those based on usability - do not occur after significant work has been done to shape vehicle components and bolt patterns. Low fidelity mockups have not been as successful for assessing certain types of activities such as use and cleaning of the waste management system (WMS), accessing cleaning tissues, and evaluating other hygiene related activities, however even the low fidelity mockup was showing that there could be a concern with having adequate volume for feet and legs while using the WMS.

VIII. Conclusion

Recognition of what operational concepts drive design and systems engineering requirements will prevent more costly adjustments later in the design and development process. Such recognition also brings the understanding of which mission concept adjustments would drive vehicle design changes. The sooner human factors aspects are integrated into the process, the more robust the resulting vehicle and crew system capability will be. Many of the challenges faced not just in Orion but in most vehicles (air, land, sea, or space) are easier to accommodate if identified and addressed early in the design process. When human factors issues emerge late in the design process,

there are generally fewer options available and those tend to be more expensive and less capable than what could have been accommodated earlier.

Flying to trans-lunar space carries with it the standard crewed vehicle challenges of designing for appropriate space for the transiting crew, but also introduces additional risks due to the inability to easily return to Earth in contingency situations. The addition of the asteroid mission introduces additional complexities and operational challenges for the crew due to the planned EVAs, sample collections, and longer mission.

The Orion is intentionally a small spacecraft compared to the Space Shuttle, which places some limitations on the capabilities of the vehicle to provide the human factors and human health capabilities to support its crew. Other limitations have been built into the vehicle as a result of the design reference missions used to baseline spacecraft requirements. These limitations correspondingly scope how the vehicle may be used in both current and future operational paradigms. In some missions, Orion will function as an independent spacecraft, operating as the sole pressurized volume for a human space mission. However, in other missions it will be necessary to supplement Orion with additional pressurized volumes, whether in the form of logistics modules, space habitats, function-specific modules, or other volumes as dictated by the desired resulting mission capability. Adjustments to the changing mission concepts will continue to be assessed and evaluated against the vehicle performance capabilities.

Understanding how the human interface and interaction considerations drive the vehicle design and operations will not only improve the vehicle but also protect needed capabilities for subsequent missions.

Acknowledgments

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